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Multiparametric observation of volcanic lightning: Sakurajima Volcano, Japan

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Key Points:
- Systematic multiparametric observations of volcanic lightning are presented for the first time
- Turbulent jets cause ash charging and clustering, promoting early plume electrical discharges
- Vent discharges are not influenced by atmospheric conditions and are relevant for early warning

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2
- Movie S3
- Movie S4

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Abstract We recorded volcanic lightning generated by Vulcanian explosions at Sakurajima Volcano using a synchronized multiparametric array. Physical properties of lightning are related to plume dynamics, and associated electromagnetic field variations are revealed by video observations (high speed and normal speed) together with infrasound and high sampling rate magnetotelluric signals. Data show that volcanic lightning at Sakurajima mainly occurs in the plume gas thrust region at a few hundred meters above the crater rim, where the overpressure of the turbulent volcanic jets determines the electrification of particles generating a complex charge structure in the growing plume. Organization of charges may be achieved at later stages when the plume transitions from the jet phase to the convective phase. Comparison with atmospheric sounding and maximum plume height data show that the effect of hydrometeors on flash generation at Sakurajima is negligible and can be more prudently considered as an additional factor contributing to the electrification of volcanic plumes.

1. Introduction

Volcanic lightning occurs in eruptive plumes as the result of the electrification of ash. Evidence is mounting that electrification is a common process in explosive eruptions in the form of a growing number of volcanic lightning reports from recent eruptions (Eyjafjallajökull 2010, Grimsvötn 2011, Puyehue 2011, Kirishima 2011, Etna 2013, Sinabung 2014, Villarica 2015, Calbuco 2015, Colima 2015, and Etna 2015). Those reports complement numerous historical reports of similar phenomena [*McNutt and Williams*, 2010].

To date, volcanic lightning has been mainly detected via electric field changes [*Anderson et al*., 1965; *James et al*., 1998; *Miura et al*., 2002] and via radio frequency radiation generated by the plume electrical activity [*Bennett et al*., 2010; *Thomas et al*., 2010; *Behnke et al*., 2013]. Thus, volcanic lightning may provide a valuable monitoring tool for active volcanoes, allowing detection of ash emissions from safe distance and in inclement weather conditions [*Behnke and McNutt*, 2014]. However, the use of volcanic lightning to probe the properties of volcanic plumes (ash concentration, mass eruption rate, turbulence, etc) has been hampered so far largely by (i) the lack of systematic instrumental observation of electric activity in volcanic plumes and (ii) the limited number of experimental investigations on the electrification processes of volcanic materials [*James et al*., 2000; *Houghton et al*., 2013; *Méndez-Harper et al*., 2015] and the mechanism of plume electrification [*Cimarelli et al*., 2014].

We present here the first results of the high-speed (HS) video recording of volcanic lightning, paired to synchronized magnetotelluric (MT) and infrasound recordings of volcanic explosions associated with electrical activity at Sakurajima Volcano. We report quantitative measurements on the physical properties of lightning discharges and their occurrence with respect to the observed plume dynamics. We compare our observations with maximum plume height measurements and atmospheric soundings and derive conclusions concerning the atmospheric conditions that are favorable for the occurrence of volcanic lightning.

2. Methodology and Results

2.1. Target Volcano and Instrumentation

Sakurajima Volcano (southern Kyushu, Japan) is one of the world's most active andesitic volcanoes. The active Showa crater (Figure 1) has been persistently erupting since 2009 with an exceptionally high rate of explosions

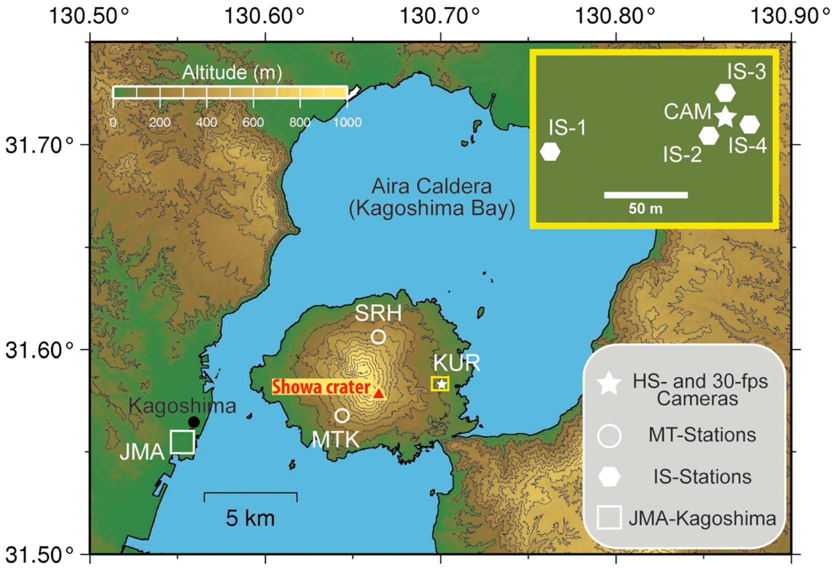

Figure 1. Location of monitoring array at Sakurajima Volcano. Insert shows position of HS and 30 fps cameras (CAM) and microphones (IS1-4) at Kurokami Observatory (KUR). SRH and MTK indicate position of magnetotelluric stations. JMA shows the location of Japan Meteorological Agency branch office in Kagoshima from where weather balloons are launched at 12 h intervals.

(Japanese Meteorological Agency, JMA reports). Cyclic Vulcanian to violent Strombolian explosions at Showa crater [*Yokoo et al*., 2013] are very often accompanied by electrical discharges associated with the generation of ash-rich plumes up to 8 km in height.

An instrumental array (Figure 1) consisting of two high-speed cameras (Phantom v711 and v710, recording at 1 and 3 kHz, respectively) and one HDD video camera (KP-DE500 Hitachi Kokusai Electric Inc., 30 Hz) in the visible range, two magnetotelluric (MT) stations (Metronix ADU07, 65 kHz), and four microphones (SI102 Datamark, 0.1 to 10 kHz) was operated continuously for 10 days (27 October to 5 November 2013). The instruments were synchronized on GPS time with microsecond accuracy and were in continuous recording mode with the exception of the HS cameras that were triggered manually at the occurrence of visible flashes. With the exception of the two MT stations, all of the instrumentation was deployed at the Kurokami branch of the Sakurajima Volcano Observatory (Figure 1), a location with direct view of the crater (along a 3.5 km direct line of sight). In addition, we used weather balloon soundings data retrieved at 12 h intervals from the local Japanese Meteorological Agency (JMA) office of Kagoshima (approximately 6 km away from Showa crater; Figure 1) (Japan Meteorological Agency, 2013, http://www.data.jma.go.jp/obd/stats/etrn/upper/index.php?year=&month=&day=&hour=&view=&point=47827), as well as data on the maximum plume altitude from the Tokyo Volcanic Ash Advisory Center (Volcanic Ash Advisory Center Tokyo, 2013, http://ds.data.jma.go.jp/svd/vaac/data/Archives/2013_vaac_list.html), to correlate the occurrence of volcanic lightning to atmospheric conditions and plume height.

2.2. Observations

The observed volcanic activity consisted of repeating cycles of impulsive Vulcanian explosions producing jets 100 to 350 m above the crater rim, which develop into buoyant plumes rising up to 6 km above sea level (asl). During the field campaign the bottom of the crater was determined to be about 90 m below the southern rim of Showa crater (Japanese Ministry of Land, Infrastructure, Transport and Tourism). Explosions were accompanied by the ejection of meter-sized ballistics and often generated powerful shock waves (Table S1 in the supporting information) audible at distances of several kilometers. Ballistic projectiles were ejected with velocities up to 120 m s^{-1} (as derived from HS video analysis). Explosions were often followed by prolonged (tens of minutes to hours long) ash-venting activity [*Cole et al*., 2014], where constant emissions of dilute low-pressure gas and volcanic ash quietly stream from the crater. No electrical activity was observed during the ash-venting activity following major explosions. Waning and consequent cessation of the ash venting was always a prelude to a new energetic explosion and the start of a new eruptive cycle.

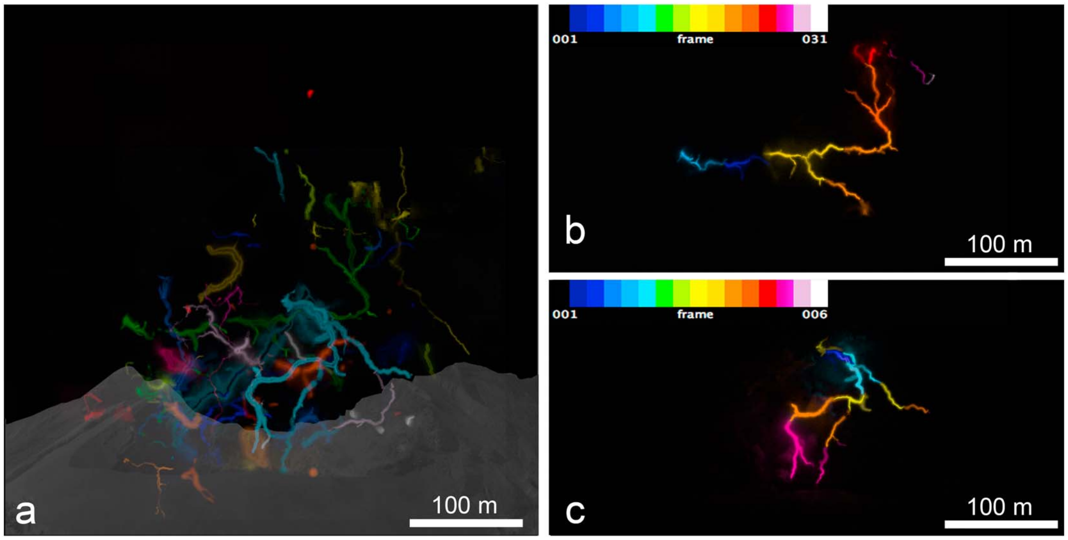

Figure 2. (a) Spatial distribution of recorded flashes above Showa crater as detected by HS videos. Color-coded images showing propagation of (b) $-$IC and (c) $-$CG flashes as captured by consecutive frames in HS videos. Flashes in Figures 2b and 2c are 31 and 6 frames long, respectively (frame interval is 333.34 μs in both images). See Text S1 in the supporting information for analysis procedure.

We observed 32 explosions and recorded a total of 144 volcanic lightning events (Table S1). The time of the explosion onset was derived by infrasound signals recorded by a microphone array located at Kurokami Observatory (Figure 1) and following the methodology of *Yokoo et al*. [2009]. Volcanic lightning events were observed and recorded during both the jetting and the convective phases of plume dynamics. Figure 2 shows the distribution of lightning flashes above Showa crater as recorded by HS videos where the extent of the discharges (350 m above the crater rim) is contained within the field of view of the HS cameras (520 × 520 m; resolution 1.5 m/pixel) and overlaps with the region of the jets generated during the explosions. We recorded only one cloud-to-ground (CG) discharge that was generated in the upper buoyant part of the plume (starting outside the field of view of the HS cameras; see Movie S3) and propagated vertically downward to discharge at the ground in proximity of the crater rim. Although flashes show no preferential direction of propagation within the plume, their prevalent mode of propagation is downward (63% downward and 37% upward). The lengths of flashes vary between 10 and 200 m, and the apparent propagation velocities of stepped leaders span between $1.3 \cdot 10^4$ and $1.2 \cdot 10^5\,\mathrm{m\,s^{-1}}$ as measured by image analysis (2-D projection) of HS videos, which is comparable to the velocity of stepped leaders in thunderstorm lightning [*Rakov and Uman*, 2003]. The duration of flashes is highly variable and largely depends on the path length of the streamers and the occurrence of return strokes (Figures 2a, 2b, and 3a). Here for total duration we refer to the time between the first appearance of the flash in the HS video and point in time when the flash stops propagating. Complete disappearance of the flash is related to the time duration of the afterglow (persisting luminosity after the return stroke), which can last up to 26 ms, as observed in HS videos. MT measurements did not detect any electromagnetic signal associated with the afterglow.

Pressure waves generated by the explosions associated with electrical activity range between <1 and 470.4 Pa (averaged over four microphones; see Table S1). Although the video recordings likely do not record all the lightning generated during a single explosion, the number of discharges recorded by the HS videos shows a positive correlation with the pressure recorded by the infrasound array at Kurokami (Figure 3c). Using the arrival times of the infrasound signal as the beginning of the explosion, we notice that flashes occur mostly at the onset of the explosion when the overpressure at the crater is larger (Figure 3).

The MT data show two main types of waveforms, each correlated with a distinct type of discharge (Figure S1). Type A consists of high-amplitude impulses with total duration of about 1 to 8 ms, while type B exhibits multiple peaks of 0.5–3 ms duration with variable times of repose between each impulse [*Aizawa et al.*, 2016]. Generally, duration of the type B discharges is much longer than that of the single pulses in the type A waveforms but shorter than the total duration of type A discharges. Through the analysis of HS videos and MT recordings, we can associate type A and type B discharges with cloud-to-ground (CG) and intracloud (IC) lightning, respectively.

The presence of graupel and the effect of ice coating become relevant on ash particles, and hence on plume electrification, at temperatures below −10°C and −20°C, respectively [*Durant et al.*, 2008; *Van Eaton et al.*, 2012]. Atmospheric profiles measured by the weather balloons show that isotherms of −10 and −20°C were stable (with minor oscillations) over the observation period at average altitudes of 6000 and 7500 m above sea level (Figure 4). In contrast, plume altitude during the 32 recorded explosions never exceeded 6 km asl (Figure 4), as reported by the Tokyo Volcanic Ash Advisory Center (VAAC) (Table S1).

Plume altitude during the 32 recorded explosions never exceeded 6 km asl as reported by VAAC Tokyo (Table S1). Atmospheric profiles measured by the weather balloons show that isotherms of −10 and −20°C were stable (with minor oscillations) at average altitudes of 6000 and 7500 m above sea level, over the observation period (Figure 4). At −10 and −20°C, the presence of graupel and the effect of ice coating respectively become relevant on ash particles [*Durant et al.*, 2008; *Van Eaton et al.*, 2012] and hence on plume electrification. In contrast, plume altitude during the 32 recorded explosions never exceeded 6 km asl (Figure 4), as reported by the Tokyo VAAC (Table S1), and were stable (with minor oscillations) at average altitudes of 6000 and 7500 m above sea level, over the observation period, respectively (Figure 4).

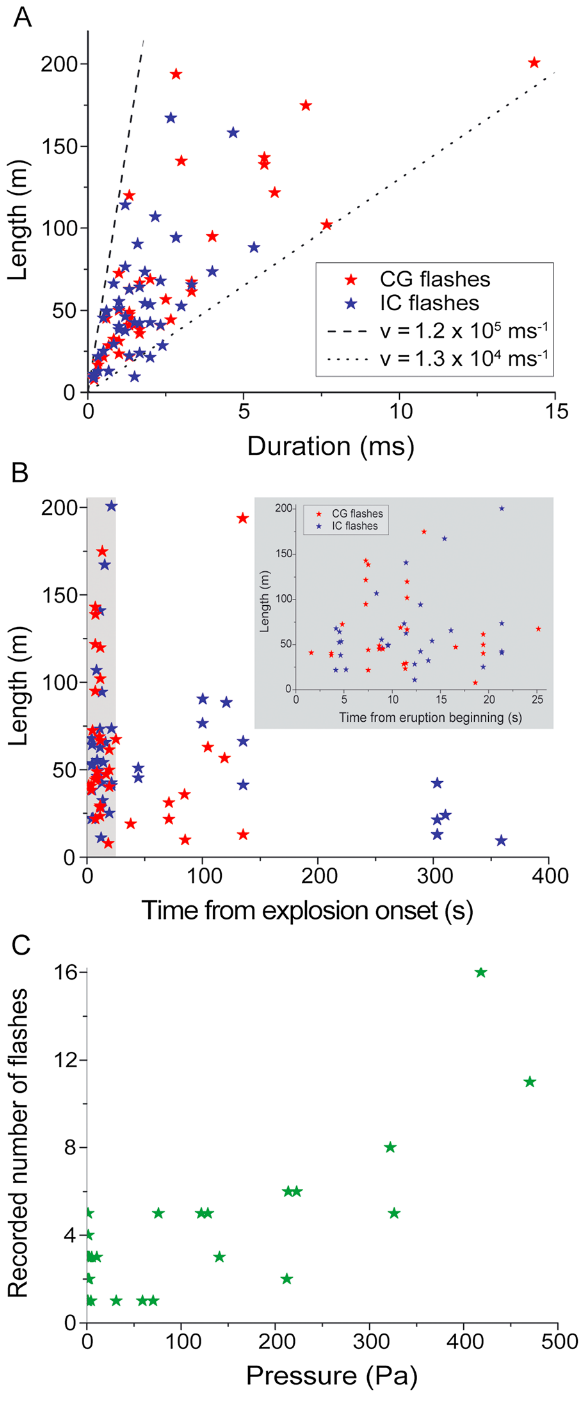

Figure 3. (a) Apparent (2-D) length of the 144 recorded flashes (maximum distance between initial and final spot) as a function of their duration (time between the first appearance of the flash until flash stops propagating in the HS video). (b) Correlation between length of flashes and time of occurrence with respect to the explosion onset (as marked by first arrivals of infrasound signals). The gray inset shows a magnification of the first 25 s of the plot. Most of the flashes occur in the first 21 s after the eruption onset, whereas in later stages flashes are less frequent. (c) Number of flashes recorded with the HS cameras as a function of the maximum average pressure (IS stations, Figure 1). Although HS cameras could not record all visible flashes, a clear positive correlation exists between number of recorded flashes and maximum pressure peak. Note that many of the explosive events also generated powerful shock waves.

3. Discussion

Explosions at Showa crater show a strongly impulsive character with long repose times of hours between each explosion. These characteristics,

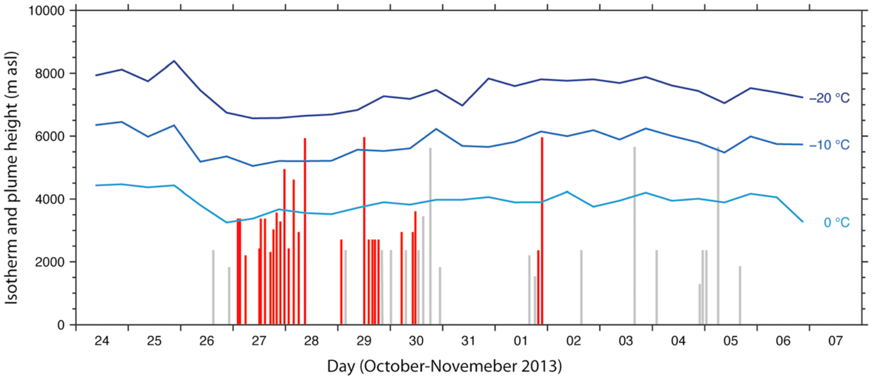

Figure 4. Comparison between plumes altitude (gray and red bars) and altitude of 0, −10, and −20°C isotherms (blue lines) during the observation period. Red bars mark plumes associated with lightning (also reported in Table S1). Gray bars represent plumes with no visible lightning.

combined with the high eruptive frequency of Sakurajima Volcano, make it an ideal setting for the study of volcanic lightning. Plumes generated at Showa crater are the result of sudden decompression of the magmatic system which generates short-duration (few to tens of seconds) and highly turbulent jets of gas and pyroclasts, sustained by the momentum imparted by the gas overpressure at the vent. Jets rise quickly to some tens to hundreds of meters above the vent rising above the crater rim at velocities up to 130 m s^{-1} (where they become visible from the Kurokami Observatory). They then decelerate rapidly under the effect of gravity and the drag of the surrounding atmosphere. The entrainment of air into the jets, which is subsequently heated and the consequent reduction in plume density, drives the transition from the gas thrust phase into the convecting phase which is characterized by a negative density contrast with the surrounding atmosphere due to the slow expansion of hot air and volcanic gases.

We observed flashes primarily at near-vent elevations (generally up to 350 m above the crater rim) before the gas thrust-to-buoyant transition. Following the classification of *Thomas et al*. [2010], the lightning discharges reported in this study would hence correspond to "vent discharges" and "near-vent flashes." At Sakurajima, the discharge rate decreases after the transition to the buoyant plume where longer flashes are occasionally generated in the higher portion of the plume ("plume lightning" of *Thomas et al*. [2010]). The vent discharges recorded in this study do not show a preferred direction of propagation. Instead, they are dendritic and show a notable tortuosity (see Movies S1 and S2). IC lightning discharges follow especially complex paths before neutralization is achieved (Figures 2a and 2b). Although flashes tend either to be confined to within the plume or to propagate along its margin, flashes propagating outward from inside the plume and neutralizing into the ambient atmosphere have also been observed (Movie S4). All of these characteristics contribute toward a complex distribution of charges within and around the plume. This is particularly relevant during the jet phase of the explosion, where particles of different sizes may segregate by dynamic processes according to their Stokes number ($St = t_p/t_f$, where t_p is the time required for a particle to obtain a velocity of 63% of the fluid velocity and t_f is a characteristic flow timescale) and where small particles ($St < 1$) follow vortical eddy structures, whereas larger particles ($St > 1$) are dominated by inertia and thus do not follow eddy trajectories [*Longmire and Eaton*, 1992]. This phase at Sakurajima corresponds to the generation of short (up to 200 m long) discharges, which have no preferential direction of propagation and neutralize by the connection of regions of charge concentrations (clusters), which are randomly distributed within the turbulent jet. MT measurements generally show a higher number of type B versus type A flashes [*Aizawa et al*., 2016]. Analysis of CG flashes reveal a prevalence of +CG (34.3%) with respect to −CG (65.6%) over the total number of observed discharges, differing thereby substantially from the common patterns observed in thunderstorms where −CG discharges constitute about 90% of the total CG discharges [*Rakov and Uman*, 2003].

The electrification experiments of particle-laden jets by *Cimarelli et al*. [2014] show characteristics very similar to the explosions observed here at Sakurajima Volcano. In those experiments particle-laden jets were produced by sudden decompression of gas and volcanic ash in a shock tube. Experimentally, flashes are generated at a condition of overpressure at the exit nozzle, which promotes the segregation of particles of different sizes in the jet phase (larger particles ($St > 1$) tend to be confined in the core of the jet, while smaller ones ($St < 1$) are accelerated toward its margins). The clustering of particles determines the charge distribution. Furthermore, these experiments clearly demonstrate that the number of discharges depends on the abundance of fine-ash particles in the jet. In the case of Sakurajima Volcano, this condition is consistent with the amount of fine-ash fallout observed in the proximity (<3 km) of the crater. These observations suggest that mechanisms similar to those inferred to be operating in the experiments are operating in the jet phase of volcanic plumes at Showa. They result in a complex distribution of electrical charges, which in turns determines the complexity of the propagation paths of flashes.

In thunderclouds, it is apparent that complex variations of electric field (characterized by constant pulses with no quiescent periods showing both positive and negative pulses) occur during the early stages of IC discharges [*Kitagawa and Brook*, 1960]. This complexity is attributed to the simultaneous progression of many streamers, reflecting the complexity of charge distribution in the cloud, which is in turn closely connected to the cellular nature of the cloud structure. Notably, similar relationships between electrical and kinematic properties in both thunderstorms and volcanic plumes have been reported by *Behnke and Bruning* [2015], consistent with the idea that particle collision in the turbulent jet is a fundamental parameter determining the charge distribution and discharge rate of a growing plume. More extensive studies should confirm that IC discharges are more frequent during the jet phase of the plume when the charges are not yet well organized. Notably, however, the ground proximity of charged jets in volcanic plumes can promote CG instead of IC discharges. This is often the case in volcanic plumes which expand upward with respect to the geometry of the surrounding crater (or vent) and/or the surrounding topography. At Sakurajima, jets are generated at the bottom of a 90 m deep crater, enabling the possibility of flash discharge to the crater walls or the rim in the early phases of the explosion.

Organization of charges may generally be observed at a later stage during the evolution of the plume when fine particles, which tend to be transported higher up by the convection of hot gases, are separated from the coarser particles thereby generating a dipole or a tripole [*Miura et al.*, 2002]. At Sakurajima this process is achieved at times of seconds to minutes after the inception of the explosion [*Aizawa et al.*, 2010]. Using the arrival time of the infrasound signals as the beginning of the explosion, we note that the majority of lightning initiates within 30 s after the beginning of the explosion and that generally longer discharges are generated later on during the evolution of the plume (Figure 3b). The generation of short flash discharges some minutes after the inception of the explosion (Figure 3b) is correlated to the injection of successive weaker jets into the already growing plume. Although we cannot exclude the occurrence of very small electrical discharges (centimeters to meters long) during the early stages of the plume formation, our observations show that the maximum length of volcanic lightning is generally a function of the plume height.

Considering the mechanism of charge generation, it should be noted that magma fragmentation at Showa is typically caused by the disruption of a plug of semisolidified magma at shallow level in the conduit [*Yokoo et al.*, 2013] and/or a lava dome plugging the bottom of the crater. That this process is very efficient is demonstrated by the very small grain size (few tens of microns) of the ash ejected, as shown by the fine-ash fallout depositing in the proximity of the crater. Thus, it is difficult to distinguish the relative contributions of tribocharging and fractocharging which are considered the main mechanisms of ash electrification in volcanic plumes [*James et al.*, 2000; *Houghton et al.*, 2013]. During the prolonged activity of ash venting at Showa crater, no visible flashes were recorded. During these mild explosive phases ash is generated by magma fragmentation and streamed out of the vent but the flow pressure and the mass flux of the gas-particle mixture are highly reduced with respect to the more energetic explosive phases. Accordingly, the kinetic energy of colliding particles is lower and the tribocharging of particles is consequently limited. This observation is consistent with experimental results [*Cimarelli et al.*, 2014], whereby overpressure at the vent, promoting the collision between particles, is inferred to be a fundamental condition for the electrification of the ejected particles.

Finally, it has been suggested that the presence of graupel in the upper portion of the plume might significantly contribute to lightning [*Arason et al.*, 2011]. Critical plume top temperatures are around −20° C. Here we note that electrification and discharge at Sakurajima are achieved in the early stage of evolution of the plume where the high temperatures (hundreds of °C) of the gas-particle mixture prevent the formation of hydrometeors [*Schill et al.*, 2015]. During our observations, ash plumes never exceeded the altitude at which ash-graupel interaction is expected to occur (Figure 4), confirming that generally volcanic lightning is primarily controlled by the dynamics of the plume and the resulting distribution of charges.

4. Conclusions

We present the first high-speed observations of volcanic lightning and pair them with MT and infrasound recordings of the explosive activity at Sakurajima Volcano. This multiparametric observation set is revealed to be necessary for advancing the understanding of the occurrence of volcanic lightning with respect to the structure of the volcanic plumes responsible for their generation.

These data lead us to infer that although volcanic and thundercloud lightning share many common physical characteristics, the conditions presaging the occurrence of electrical discharges at explosive eruptions result from the complex charge distribution within the developing plume. Particle segregation by turbulent flow in volcanic jets promoted by the gas overpressure at the vent is responsible for the early electrification of particles and for the chaotic distribution of charges in the growing plume, which promote short discharges with tortuous paths and no preferential direction of propagation. The maximum length of lightning flashes increases with time from the onset of the explosion. Organization of charges may be achieved at later stages when the plume transitions from the jet phase to the convective phase, which possibly promotes the generation of longer, more vertical cloud-to-ground flashes. The effect of hydrometeors on flash generation at Sakurajima during the period of our observations is negligible. At Sakurajima as well as at other volcanoes the electrification seems to be primarily determined by the plume dynamics. In contrast, the occurrence of hydrometeors in the plume can be more generally considered an additional factor that can contribute to the electrification of ash when favorable atmospheric conditions are met. In light of our results we can further state that multiparametric monitoring of electrical activity at active volcanoes not only can readily signal the presence of ash in the atmosphere during volcanic unrest but also can provide additional information on the time evolution of volcanic plumes.

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